

ON THE MASS OF THE DARK COMPACT OBJECTS IN THE GALACTIC DISK

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Abstract

Recently the Polish-American collaboration OGLE has reported the observation of four possible microlensing events by monitoring, over several months, the brightness of millions of stars in the region of the galactic bulge. If these events are due to microlensing, the most accurate way to get information on the mass of the dark compact objects, that acted as gravitational lenses, is to use the method of the mass moments. Here I apply this method to the analysis of the events detected by OGLE. The average mass turns out to be $0.28M_{\odot}$, suggesting that the lens objects are faint disk stars. The same method applied to the five microlensing events detected so far by the EROS and MACHO collaborations, which monitor stars in the Large Magellanic Cloud, leads to an average value of $0.08M_{\odot}$ for the dark compact halo objects.

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1. Introduction

An important problem in astrophysics is the nature of the non-luminous matter in which galaxies are embedded. Its presence is inferred from the shape of the measured rotation curves. It is well possible that the dark matter in the halo and in the disk of the galaxies is made of “brown dwarfs” or Jupiter-like bodies, which are aggregates of the primordial elements: hydrogen and helium, and have masses in the range $O(10^{-7}) < M/M_{\odot} < O(10^{-1})$ (De Rújula et al. 1992). Paczyński suggested a way to detect such objects in the halo and in the disk of our own galaxy using the gravitational lens effect (Paczynski 1986, 1991; Griest et al. 1991).

Recently the French collaboration EROS (Aubourg et al. 1993) and the American–Australian collaboration MACHO (Alcock et al. 1993) reported the possible detection of altogether five microlensing events, discovered by monitoring over several years millions of stars in the Large Magellanic Cloud (LMC), whereas the Polish-American collaboration OGLE (Udalski et al. 1993) has found four microlensing events by monitoring stars located in the galactic bulge.

If these observations are true microlensing events, an important question is to determine the mass of the dark compact objects, that acted as gravitational lenses. This knowledge is also relevant in order to infer the amount of dark matter in our galaxy and in its halo. The most appropriate way to compute the average mass is to use the method of mass moments developed by De Rújula et al. (1991).

Here I apply this method to the four events detected by OGLE by looking at the galactic bulge and to the ones of EROS and MACHO in the LMC. I also compute for each event the value of the most likely mass of the lens object. Of course the very small number of observations at our disposal does not yet allow a precise determination of the mass distribution, so that the present results are preliminary. Nevertheless, it shows how in practice it will be possible to get precise information, as soon as a sufficient number of microlensing events will be available, on the mass distribution as well as on what fraction they contribute to the total dark mass in the halo or in the disk of our galaxy. In the following I will use the formulas and the notation derived in De Rújula et al. (1991), to which I refer for more details on the derivation; I refer to the paper by Jetzer & Massó (1994) as well, where the first three discovered events in the LMC are discussed.

2. Microlensing rates

First I compute the microlensing rate Γ for an experiment monitoring stars in the galactic bulge in Baade’s window of galactic coordinates (longitude and latitude): $l = 1^{\circ}$, $b = -3.9^{\circ}$.

Let d be the distance of the massive halo or disk object (MHO) to the line of sight between the observer and a star in the galactic bulge, $t = 0$ the instant of closest approach, and v_T the MHO velocity in the transverse plane. The magnification A as a function of time is calculated using simple geometry, and is given by

$$A(t) = A[u(t)] = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}} , \quad (1)$$

where

$$u^2 = \frac{d^2 + v_T^2 t^2}{R_E^2} . \quad (2)$$

The light curve is a universal function determined by the two parameters d/R_E and v_T/R_E . R_E is the Einstein radius, which is

$$R_E^2 = \frac{4GMD}{c^2} x(1-x) = r_E^2 \mu x(1-x) , \quad (3)$$

with M (respectively μ) the MHO mass (in M_\odot solar mass units) and D (xD) the distance from the observer to the source (to the MHO); $D = 8.5$ kpc is the distance to stars in the galactic bulge, and $r_E = 1.25 \times 10^9$ km. I use here the definition: $T = R_E/v_T$ (this is slightly different from the definition used in De Rújula et al. (1991)).

The number density of disk stars per unit mass is given by (Bahcall & Soneira 1980)

$$\frac{dn}{dM} = \frac{dn_0}{dM} \exp \left(-\frac{Dx |\sin b|}{300 \text{ pc}} + \frac{Dx \cos b}{3.5 \text{ kpc}} \right) = \frac{dn_0}{dM} H_d(x) , \quad (4)$$

where the galactic longitude $l = 0^\circ$ has been adopted and $\frac{dn_0}{dM} = \frac{\rho_d(M)}{M}$ with $\rho_d(M) = 0.05 M_\odot \text{ pc}^{-3}$; H_d can be written as follows

$$H_d(x) = \exp \left(\frac{x D (1 - 11.7 |\sin b|)}{3.5 \text{ kpc}} \right) , \quad (5)$$

using also the fact that $\cos b \approx 1$ for the galactic bulge.

For the contribution of the halo dark matter in the form of massive objects (MHO) located in the disk I use the following distribution for the number density per unit mass dn/dM

$$\frac{dn}{dM} = H_h(x) \frac{dn_0}{dM} = \frac{a^2 + R_{GC}^2}{a^2 + R_{GC}^2 + D^2 x^2 - 2DR_{GC}x \cos \alpha} \frac{dn_0}{dM} , \quad (6)$$

with dn_0/dM the local dark mass number density. The local dark mass density is $\rho_0 \simeq 8 \times 10^{-3} M_\odot \text{ pc}^{-3}$. It is assumed that dn/dM factorizes in functions of M (or μ) and x . The galactic core radius is $a = 5.6$ kpc, whereas $R_{GC} = 8.5$ kpc is our distance from the centre of the galaxy, and $\alpha \simeq 4^\circ$ is the angle between the line of sight and the direction of the galactic centre.

In computing Γ one must also take into account the fact that both the source and the observer are in motion (Griest 1991; Griest et al. 1991). Relevant are only the velocities transverse to the line of sight. The transverse velocity of the microlensing tube at position xD is: $\vec{v}_t(x) = (1-x)\vec{v}_{\odot\perp} + x\vec{v}_{s\perp}$, and its magnitude is

$$v_t(x) = \sqrt{(1-x)^2 |\vec{v}_{\odot\perp}|^2 + x^2 |\vec{v}_{s\perp}|^2 + 2x(1-x) |\vec{v}_{\odot\perp}| |\vec{v}_{s\perp}| \cos \theta} , \quad (7)$$

where $\vec{v}_{s\perp}$ and $\vec{v}_{\odot\perp}$ are the source and the solar velocities transverse to the line of sight and θ the angle between them.

For the velocity distribution of the MHOs or the faint disk stars I consider an isothermal spherical model, which in the rest frame of the galaxy is given by

$$f(\vec{v}) d^3 v = \frac{1}{\tilde{v}_H^3 \pi^{3/2}} e^{-\vec{v}^2/\tilde{v}_H^2} d^3 v . \quad (8)$$

Since only the transverse velocities are of relevance cylindrical coordinates can be used and the integration made over the velocity component parallel to the line of sight. Moreover, due to the velocities of the observer and the source, the value of the transverse velocity gets shifted by $\vec{v}_t(x)$. The distribution for the transverse velocity is thus

$$\tilde{f}(v_T)dv_T = \frac{1}{\pi v_H^2} e^{-(\vec{v}_T - \vec{v}_t)^2/v_H^2} v_T dv_T , \quad (9)$$

where v_H is the velocity dispersion for which I adopt the value $v_H \approx 30 \text{ km s}^{-1}$ (Paczynski 1991). The random velocity of the source stars are again described by an isothermal spherical distribution, whose transverse velocity distribution is

$$g(v_{s\perp})dv_{s\perp} = \frac{1}{\pi v_D^2} e^{-v_{s\perp}^2/v_D^2} v_{s\perp} dv_{s\perp} , \quad (10)$$

where $v_D = 156 \text{ km s}^{-1}$ is the velocity dispersion (Mihalas & Binney 1981; Paczynski 1991; Griest et al. 1991).

Taking all the above facts into account, Γ turns out to be (De Rújula et al. 1991; Griest 1991)

$$\begin{aligned} \Gamma = & 4 r_E D v_H u_{TH} \left(\int_0^\infty \sqrt{\mu} \frac{dn_0}{d\mu} d\mu \right) \int_0^{2\pi} d\theta \int_0^\infty dv_{s\perp} g(v_{s\perp}) \\ & \int_0^1 \sqrt{x(1-x)} H_i(x) e^{-\eta^2} \int_0^\infty dy y^2 I_0(2y\eta) e^{-y^2} , \end{aligned} \quad (11)$$

where $y = \frac{v_T}{v_H}$, $\eta(x, \theta, v_{s\perp}, v_{\odot\perp}) = \frac{v_t}{v_H}$, and I_0 is the modified Bessel function of order 0. In the limit of stationary observer and source star ($v_{\odot\perp} = v_{s\perp} = 0$), $\eta = 0$ and $I_0 = 1$; H_i means either H_d or H_h ; u_{TH} is related to the minimal experimentally detectable magnification $A_{TH} = A[u = u_{TH}]$; $v_{\odot\perp}$ is $\approx 220 \text{ km s}^{-1}$ (more precisely it should be multiplied by $\cos l$, where l is the galactic longitude but since $l = 1^\circ$, $\cos l \approx 1$). In computing Γ one should also take into account the limited measurable range for the event duration T , which translates into a modification of the integration limits. A fact that can be described by introducing an efficiency function $\epsilon(\mu)$ (De Rújula et al. 1991). However for the range of interest here, $\epsilon(\mu) \approx 1$, and thus I will neglect it in the present calculations.

For an experiment monitoring N_\star stars during a total observation time t_{obs} the number of expected microlensing events is

$$N_{ev} = N_\star t_{obs} \Gamma . \quad (12)$$

Assuming a delta-function-type distribution for the masses

$$\frac{dn_0}{d\mu} = \frac{\rho}{M_\odot} \frac{\delta(\mu - \bar{\mu})}{\mu} , \quad (13)$$

eq. (11) can be integrated. With $N_\star = 10^6$ stars and $t_{obs} = 1$ year one gets

$$N_{ev} = 2.08 \sqrt{\bar{\mu}} \left(\frac{\rho_d}{5 \times 10^{-2} M_\odot \text{ pc}^{-3}} \right) u_{TH} , \quad (14)$$

for $H_i = H_d$, and

$$N_{ev} = 0.61 \sqrt{\bar{\mu}} \left(\frac{\rho_0}{8 \times 10^{-3} M_\odot \text{ pc}^{-3}} \right) u_{TH} , \quad (15)$$

for $H_i = H_h$. The numerical factor in eq. (14) for N_{ev} as a function of b , the galactic latitude, varies between 6.8 for $b = 0^\circ$ and 1.9 for $b = 5^\circ$, whereas the factor for N_{ev} of eq. (15) remains practically unchanged.

3. Most likely mass and mass moments

The probability P that a microlensing event of duration T and maximum amplification A_{max} be produced by a MHO or a faint disk star of mass μ can be derived starting from eq. (11) (Jetzer & Massó 1993) and leads to

$$P(\mu, T) \propto \frac{\mu^2}{T^4} \int_0^{2\pi} d\theta \int_0^\infty dv_{s\perp} g(v_{s\perp}) \int_0^1 dx (x(1-x))^2 H_i(x) e^{-\eta^2} \exp\left(-\frac{r_E^2 \mu x(1-x)}{v_H^2 T^2}\right) I_0\left(2\eta \frac{r_E \sqrt{\mu x(1-x)}}{v_H T}\right) . \quad (16)$$

One sees that $P(\mu, T) = P(\mu/T^2)$, and that it does not depend on the value of A_{max} . In table 1, P is listed for the four events of OGLE for H_d ; in table 2 the corresponding values for the MACHO and EROS events are given, which are computed using the corresponding formula for $P(\mu, T)$ as discussed in Jetzer & Massó (1994).

The normalization of P is arbitrarily chosen such that the maximum of $P(\mu_{MP}, T) = 1$, and μ_{MP} is the most probable value. The maximum corresponds to $\mu r_E^2 / v_H^2 T^2 \simeq 213$ for H_d and $\simeq 196$ for H_h . For the LMC the maximum corresponds to $\mu r_E^2 / v_H^2 T^2 = 13.0$ (with $v_H = 210 \text{ km s}^{-1}$ and $r_E = 3.17 \times 10^9 \text{ km}$). The 50% confidence interval embraces for the mass μ approximately the range $1/3\mu_{MP}$ up to $3\mu_{MP}$.

A more systematic way to extract information on the masses is to use the method of moments as discussed in De Rújula et al. (1991). The moments $\langle \mu^m \rangle$ are given by

$$\langle \mu^m \rangle = \int d\mu \frac{dn_0}{d\mu} \mu^m , \quad (17)$$

and $\langle \mu^m \rangle$ is related to $\langle \tau^n \rangle = \sum_{events} \tau^n$, with $\tau \equiv (v_H/r_E)T$, as constructed from the observations by

$$\langle \tau^n \rangle = \int dN_{ev} \tau^n = V u_{TH} \gamma_i(m) \langle \mu^m \rangle , \quad (18)$$

with $m \equiv (n+1)/2$ and

$$V \equiv 4N_\star t_{obs} D r_E v_H , \quad (19)$$

$$\gamma_i(m) \equiv \int_0^{2\pi} d\theta \int_0^\infty dv_{s\perp} g(v_{s\perp}) \int_0^1 dx H_i(x) (x(1-x))^m e^{-\eta^2} \int_0^\infty dy y^{3-2m} e^{-y^2} I_0(2\eta y) . \quad (20)$$

In table 3 the values of $\gamma_i(m)$ are listed for $m = 0, 0.5$ and 1 , which are the ones needed here.

Eq. (20) is also useful for computing the average duration $\langle T \rangle$ (with $T = \frac{r_E}{v_T} = \frac{r_E}{v_T} \sqrt{\mu x(1-x)}$) for a microlensing event defined as

$$\langle T \rangle = \frac{\int dN_{ev} \frac{r_E}{v_T} \sqrt{\mu x(1-x)}}{N_{ev}}. \quad (21)$$

Assuming a delta-function-type mass distribution (eq. (13)), one finds

$$\langle T \rangle_i = \frac{r_E}{v_H} \sqrt{\mu} \frac{\gamma_i(1)}{\gamma_i(0.5)}. \quad (22)$$

For disk stars with $H_i = H_d$ one gets

$$\langle T \rangle_d \simeq 52 \sqrt{\mu} \text{ days}, \quad (23)$$

and for MHO with $H_i = H_h$

$$\langle T \rangle_h \simeq 42 \sqrt{\mu} \text{ days}. \quad (24)$$

The mean local density of MHO (number per cubic parsec) is $\langle \mu^0 \rangle$. The average local mass density in MHO is $\langle \mu^1 \rangle$ solar masses per cubic parsec. The mean MHO mass, which one gets from the four events of OGLE, using the faint disk star distribution H_d , is

$$\frac{\langle \mu^1 \rangle}{\langle \mu^0 \rangle} = \frac{\langle \tau^1 \rangle}{\langle \tau^{-1} \rangle} \frac{\gamma_d(0)}{\gamma_d(1)} \simeq 0.28 M_\odot. \quad (25)$$

If instead one uses the H_h distribution, one recovers practically the same value for the average, namely: $\langle \mu^1 \rangle / \langle \mu^0 \rangle \simeq 0.29 M_\odot$. The average value clearly suggests that these objects are faint disk stars. Notice that $\gamma_i(m)$ depends on the value of the galactic latitude b . However the ratios change much less, in particular $\gamma_d(0)/\gamma_d(1)$ varies by at most 10 to 15% by varying b from 0° to 5° , whereas $\gamma_h(0)/\gamma_h(1)$ remains practically unchanged. The same being true for the ratios $\gamma_d(1)/\gamma_d(0.5)$ and $\gamma_h(1)/\gamma_h(0.5)$.

Similarly one can also find the mean MHO mass based on the five events detected by EROS and MACHO. The corresponding values for $\gamma(m)$ are $\gamma(0) = 0.280$ and $\gamma(1) = 0.0362$ (De Rújula et al. 1991), thus giving

$$\frac{\langle \mu^1 \rangle}{\langle \mu^0 \rangle} \simeq 0.08 M_\odot. \quad (26)$$

This value is somewhat lower than the one previously computed of $0.14 M_\odot$ (Jetzer & Massó 1994), which was based on only three events. The lower value of the MHO mean mass for the halo objects indicates that they are brown dwarfs rather than low-mass stars as seems to be the case for the events detected by OGLE.

Although based on few events, these results are of interest. Clearly, once more data will be available it will be possible to get more precise information. In particular, it will be possible to determine other important quantities such as the statistical error in eq. (25) or eq. (26) and the fraction $f \equiv M_J/\rho_0 \sim 0.12 \text{ pc}^3 \langle \mu^1 \rangle$ of the local dark mass density (the latter one given by ρ_0) detected in the form of MHOs.

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Table 1: Values of the most probable mass μ_{MP} in units of M_\odot as obtained by $P(\mu, T)$ with $H_i = H_d$ and $T = \frac{R_E}{v_T}$ for the four microlensing events of OGLE. ($v_H = 30 \text{ km s}^{-1}$ and $r_E = 1.25 \times 10^9 \text{ km}$.)

	1	2	3	4
T (days)	25	45	10.7	14
$\tau(\equiv \frac{v_H}{r_E} T)$	5.2×10^{-2}	9.35×10^{-2}	2.22×10^{-2}	2.91×10^{-2}
μ_{MP}	0.57	1.85	0.105	0.18

Table 2: Values of the most probable mass μ_{MP} in M_\odot units for the five microlensing events detected in the LMC (A_i = American-Australian collaboration events ($i = 1, 2, 3$); F_1 and F_2 French collaboration events). For the LMC: $v_H = 210 \text{ km s}^{-1}$ and $r_E = 3.17 \times 10^9 \text{ km}$.

	A_1	A_2	A_3	F_1	F_2
T (days)	16.9	9	14	27	30
$\tau(\equiv \frac{v_H}{r_E} T)$	9.67×10^{-2}	5.15×10^{-2}	8.01×10^{-2}	1.54×10^{-1}	1.72×10^{-1}
μ_{MP}	0.12	0.03	0.08	0.31	0.38

Table 3: Values of $\gamma_d(m)$ (for H_d) and $\gamma_h(m)$ (for H_h) for $m = 0, 0.5$ and 1 valid for $b = -3.^\circ 9$.

m	$\gamma_d(m)$	$\gamma_h(m)$
0	252.7	390.3
0.5	14.7	27.2
1	1.6	2.4